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ANALYSIS OF NONUNIFORM SUIT TEMPERATURES FOR SPACE SUITS IN ORBIT

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6570th AEROSPACE MEDICAL RESEARCH LABORATORIES
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AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

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FOREWORD

The second phase of this investigation was conducted by Dr. Thomas F. Irvine, Jr., Dean of Engineering, State University of New York, Long Island Center, and Kenneth R. Cramer, Aeronautical Research Laboratory, Office of Aerospace Research, Wright-Patterson Air Force Base, Ohio, between November 1959 and April 1961. The first phase, conducted between May 1959 and November 1959, was reported by Irvine and Cramer in WADD TN 60-145, Thermal Analysis of Space Suits in Orbit, May 1960. The work was performed for the Aerospace Medical Research Laboratories of the Aerospace Medical Division in support of Project No. 6301, "Aerospace Systems Personnel Protection," Task No. 630104, "Space Protective Garments." Miss Elizabeth Comfort of the Protection Branch, Life Support Systems Laboratory, was the project engineer for the Aerospace Medical Research Laboratories.

The authors wish to express their appreciation to Captain Barnard Rodstein, Analysis Branch, Digital Computation Division, Aeronautical Systems Division, for performing the numerical integrations of the governing differential equation.

ABSTRACT

A cylindrical model of a space suit exposed to solar and metabolic heating is examined to determine the design criteria for minimizing equilibrium temperature differences. Resulting suit shell thicknesses are compared with those of a previous analysis that utilized the material thermal capacity and surface spectral properties to establish passive nonequilibrium temperature control. Results demonstrate that light-metal suits will develop small equilibrium temperature differences and be very heavy. Fabric suits of similar design will be even heavier. A water-filled suit shell is recommended as an attractive design approach if required circulation rates are practical. This is the second phase of an investigation to delineate the design parameters for controlling thermal environment in a space suit located in an orbit around the earth.

PUBLICATION REVIEW

This technical documentary report has been reviewed and is approved.

Wayne H. McCandless
WAYNE H. McCANDLESS
Chief, Life Support Systems Laboratory

LIST OF SYMBOLS

A	Parameter defined on page 3
A_T	Total outside area of suit - ft^2
B	Parameter defined on page 3
C	Parameter defined on page 3
c_p	Specific heat - $Btu/lb_m\ °F$
D	Outside diameter of suit - ft
k	Thermal conductivity of suit material - $\frac{Btu\ ft}{hr\ ft^2\ °F}$
L	Overall suit length - ft
M	Mass of suit - lb_m
Q	Heating rate - Btu/hr
q	Heat flux - $Btu/hr\ ft^2$
q_s	Solar heat flux, $q_s = 420\ \frac{Btu}{hr\ ft^2}$
$\overline{q}$	Nondimensional heat flux, $\overline{q} = q_m L/k\pi T_a$
t_c^{Δ}	Nondimensional time constant - defined as time at which the suit temperature drops to 90 percent of its original value
T	Temperature - °R
T_a	Reference temperature, $T_a = 540°\ R$
ΔT	Maximum temperature difference - °R
x	Coordinate parallel to suit axis - ft
α	Thermal diffusivity - ft /hr
α_s	Total absorptivity to incident solar radiation
ϵ	Total hemispherical emissivity
η	Nondimensional coordinate parallel to suit axis, $\eta = x/L$
θ	Nondimensional temperature, $\theta = T/T_a$
ρ	Suit material density - lb_m/ft
σ	Stefan-Boltzman Constant, $\sigma = 0.173 \times 10^{-8}\ Btu/ft^2\ hr\ °R^4$

LIST OF SYMBOLS (Cont'd)

τ_1	Thickness of suit material as determined by equation 7 - ft
τ_2	Thickness of suit material as determined by equation 5 - ft
m	Metabolic heating
r	Radiated heat
L	Value at x = L

ANALYSIS OF NONUNIFORM SUIT TEMPERATURES FOR SPACE SUITS IN ORBIT

INTRODUCTION

The general problem of determining the design parameters of a space suit capable of providing a satisfactory thermal environment for a man located outside his vehicle in an earth orbit was considered in the first phase of this investigation.* The large number of influencing factors and complexities necessitated the division of the general investigation into separate and more manageable parts. As the first phase of the investigation, the surface temperature variation with time was determined as a function of the suit material and surface spectral properties for a cylindrical suit model subject to the most extreme hot and cold environments. The results demonstrated that passive temperature control was feasible for a suit having an adiabatic inner surface and a uniformly distributed surface temperature. Since any chosen suit material will have a finite thermal conductivity and be subjected to a nonuniformly distributed incident heat flux, temperature differences will exist which will be intolerable if large. Therefore, this second phase of the general investigation was conducted to determine the design requirements for minimizing suit temperature differences.

ANALYSIS

The cylindrical suit model chosen in the first phase must be modified, as shown in figure 1, to include a definite suit thickness and finite thermal conductivity for providing an appropriate mathematical model for determining representative suit temperature variations. Since the maximum temperature difference is of primary concern, the suit is assumed to be subjected to solar heat flux only at one end while the remaining surfaces are radiating to empty space; i.e., 0° R (Rankine). In addition, the external heating absorbed by the total end area is assumed to be concentrated uniformly around the circumference of the shell at its initial boundary, the metabolic heating is uniformly distributed only along the inner cylindrical surface, and the suit is in thermal equilibrium with its environment--i.e., independent of time.

*Irvine, F., Jr., and K.R. Cramer, Thermal Analysis of Space Suits in Orbit, Wright Air Development Division Technical Note 60-145, Wright-Patterson Air Force Base, Ohio, May 1960.

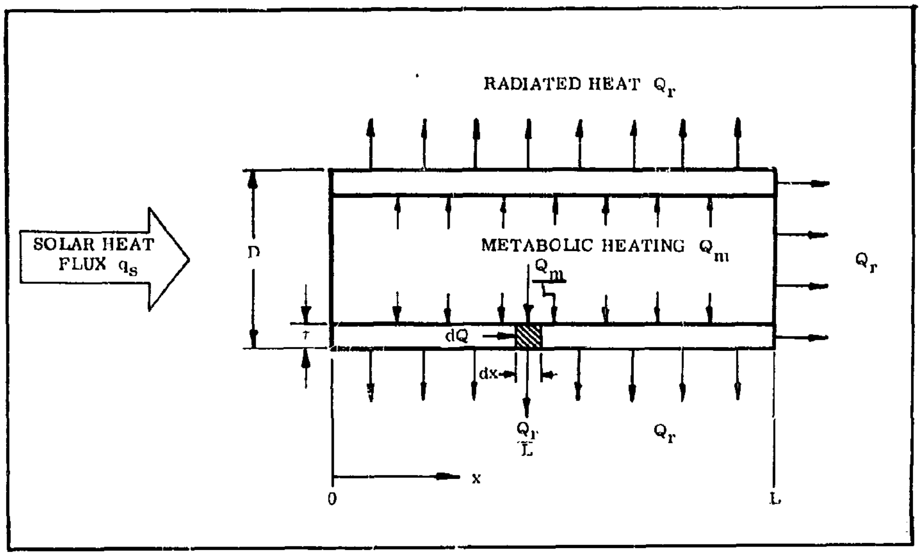

Figure 1. Analytical Suit Model

With these assumptions and the suit geometry of figure 1, the heat balance for an elemental length of the cylindrical shell is expressed by:

$$\frac{dQ}{dx} + \frac{Q_m}{L} = \frac{Q_r}{L} \tag{1}$$

Substituting the defining expressions:

$$Q = -k\pi D\tau \frac{dT}{dx}$$

$$Q_r = \sigma\epsilon\pi D L T^4$$

$$Q_m = \pi D L q_m$$

for the various heating rates, and nondimensionalizing:

$$\frac{d^2\theta}{d\eta^2} + A\theta^4 - \bar{q} = 0 \tag{2}$$

The boundary conditions for this ordinary second order differential equation can be determined by considering the heat balance with the external environment at each end:

$$\text{at } \eta = 0: \quad Q = -k\pi D\tau_2 \frac{T_a}{L}\frac{d\theta}{d\eta} = \frac{\pi D^2}{4}\alpha_s q_s$$

$$\text{or: } \left.\frac{d\theta}{d\eta}\right|_{\eta=0} = -\frac{LD\alpha_s q_s}{4k\tau_2 T_a} = -B \tag{3}$$

$$\text{at } \eta = 1: \quad Q = -k\pi D\tau_2 \frac{T_a}{L}\frac{d\theta}{d\eta} = \sigma\epsilon\frac{\pi D^2}{4} T_L^4$$

$$\text{or: } \left.\frac{d\theta}{d\eta}\right|_{\eta=1} = -\frac{LDT_a^3\sigma\epsilon}{4k\tau_2}\theta_1^4 = -c\theta_L^4 \tag{4}$$

Therefore, the solution of equation 2 subject to the boundary conditions, equations 3 and 4, will provide the temperature distribution along the cylindrical portion of the suit for various suit materials and thicknesses. The maximum temperature difference will then simply be the difference between the temperatures at the two ends.

Since solution of equation 2 by analytical methods is unlikely, it is necessary to resort to a numerical integration scheme to provide the required longitudinal temperature distribution. This numerical work is greatly reduced by the use of the relations for the various parameters:

$$A = \frac{4\sigma T_a^4 \epsilon L}{q_s \alpha_s D} B$$

$$B = \frac{LD\alpha_s q_s}{4T_a k\tau_2}$$

$$C = \frac{\sigma T_a^4 \epsilon}{\alpha_s q_s} B$$

and constants:

$$\begin{aligned} L &= 5.75 \text{ ft} \\ D &= 1.04 \text{ ft} \\ \alpha_s &= 0.12 \\ \epsilon &= 0.89 \\ Q_m &= 800 \text{ Btu/hr} \\ A_T &= 20.5 \text{ ft}^2 \end{aligned}$$

that were selected in the first phase. The number of arbitrary parameters is then reduced to one, the initial slope B which is a function of the material thickness and thermal conductivity.

The required suit shell thickness and mass can then be determined with equations 5 and 6 which were obtained from the definitions of B and mass and the assumed constants above:

$$\tau = \frac{0.1397}{kB} \tag{5}$$

$$M = \frac{2.86}{B}\frac{\rho}{k} \tag{6}$$

In the first phase the suit temperature variation with time was determined from the balance of the metabolic heating with the external environment as influenced by the heat retention capacity of the material and surface spectral properties. The shell thickness (τ_1) was determined as a function of the heat retention parameter, surface radiation properties, and a time constant which was chosen as 4 in an example problem to limit the minimum suit temperature to 62° F for a 300-mile orbit:

$$\tau_1 = \frac{\epsilon t_c{}^{\Delta}}{1.132 \rho c_p} \tag{7}$$

Therefore, with the various assumed constants, the ratio of the thicknesses or masses is a function of the material thermal diffusivity and the initial slope B:

$$\frac{\tau_1}{\tau_2} = \frac{M_1}{M_2} = 22.5\alpha B \tag{8}$$

When this ratio is greater than one, the material thickness as required by the first phase must be chosen to provide a proper thermal environment. Since this thickness is greater than that required by the present analysis, smaller equilibrium maximum temperature differences will exist. If the ratio is less than one, then the thickness computed with equation 5 must be chosen to minimize the maximum temperature difference. This thickness is greater than that computed with equation 7 and thus provides a greater thermal capacity which will lengthen the time for the suit to reach thermal equilibrium with its external environment. This ratio is useful only for the above general-type comparison since it compares the results of the time-dependent analysis of the first phase with the results of this non-time-dependent study. A more direct comparison could be made between the results of two time-dependent or two non-time-dependent analyses.

RESULTS

Equation 2, as restricted by the boundary conditions and simplifying relations, was integrated numerically with the Runge-Kutta method on a digital computer for a range of initial slopes, B. Agreement with precomputed slopes at η-1 was obtained to seven significant figures.

Figures 2 through 6 present in graphical form the numerical results for the temperature variation, maximum temperature difference, mass, thickness, and thickness ratio. The strong dependence of the temperature distribution and maximum temperature difference on the initial slope B is shown in figures 2 and 3. However, the choice of a small initial slope to reduce the maximum temperature difference also increases the shell thickness and mass as shown in figures 4 and 5. The shell thickness is a function of ρ/k and figure 5 presents results only for aluminum and copper since they have the lowest ratios. Fabrics have ratios approximately 100 times larger and would result in extremely thick and heavy suits.

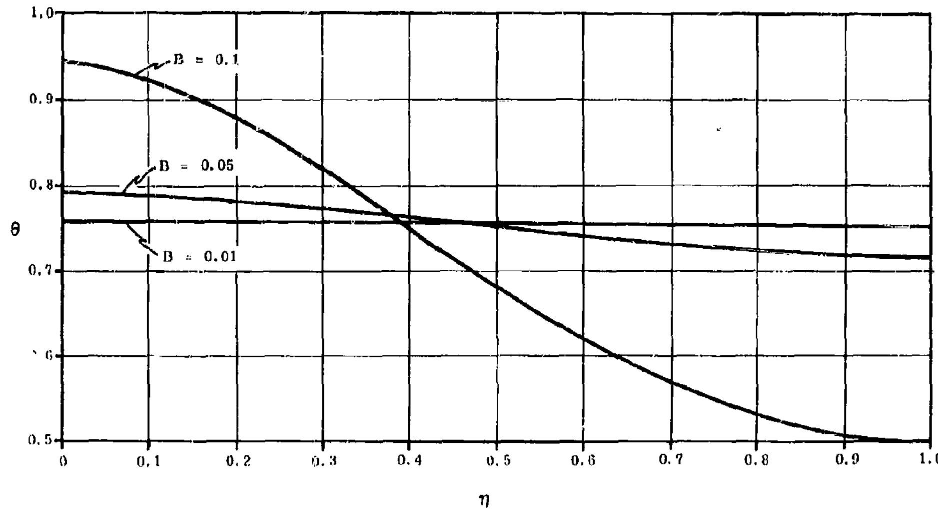

Figure 2. Suit Temperature Distribution

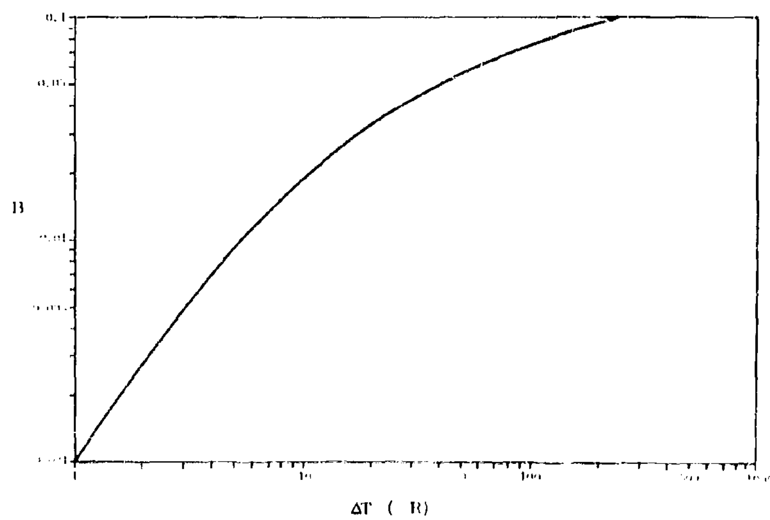

Figure 3. Maximum Suit Temperature Difference

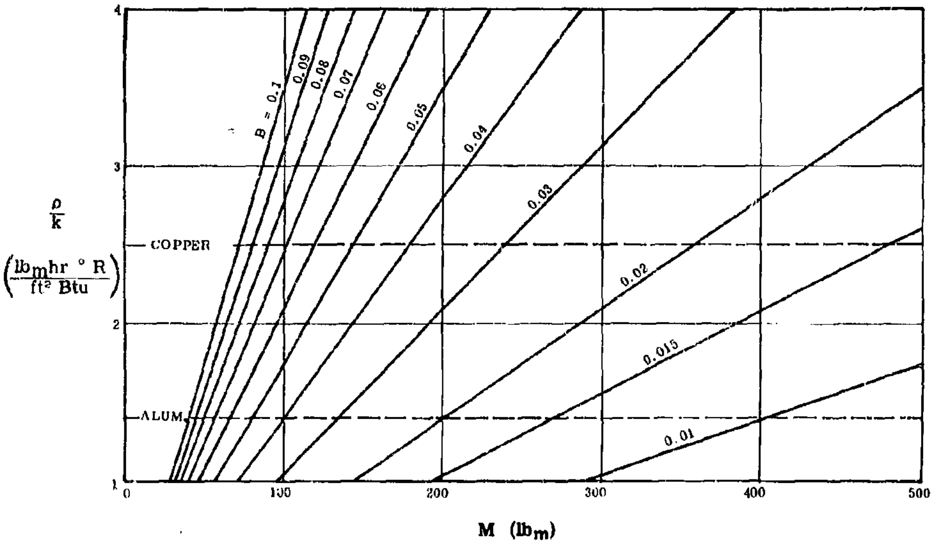

Figure 4. Suit Mass

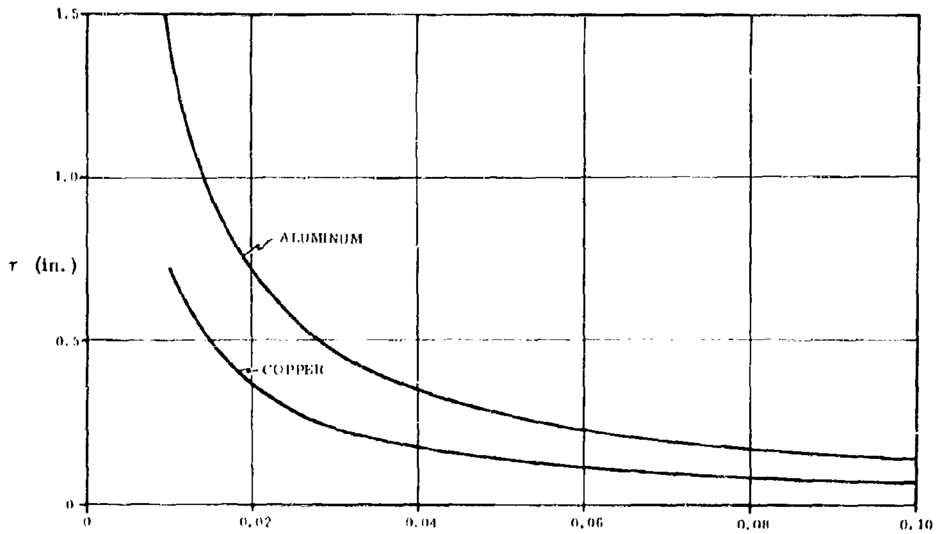

Figure 5. Suit Shell Thickness

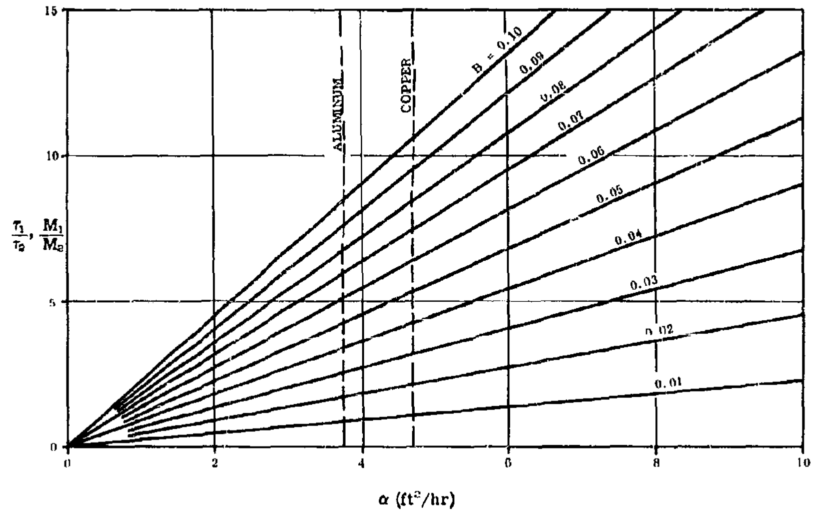

Figure 6. Thickness and Mass Ratio

The utility of the graphs and application of the general results can best be demonstrated with the following example suit problem.

Given: Maximum tolerable $\Delta T = 30° F$

To be determined: Material type, thickness, mass, and resulting maximum ΔT.

Solution:

1. With figure 3 and $\Delta T = 30° F$:
   $B_2 = 0.043$

2. With figure 4 and $B_2 = 0.043$:
   $M_2 = 95 \ lb_m$ for aluminum

3. With figure 5 and $B_2 = 0.043$:
   $\tau_2 = 0.33$ in. for aluminum

4. With figure 6 and $B_2 = 0.043$:

   $$\frac{\tau_1}{\tau_2} = \frac{M_1}{M_2} = 3.7 \text{ for aluminum}$$

5. Since $\frac{\tau_1}{\tau_2} > 1$, then the thickness τ_1 and mass M_1 must be used. Therefore,

   $$\tau_1 = 3.7 \times 0.33 = 1.22 \text{ in.}$$

   and $M_1 = 3.7 \times 95 = 352 \ lb_m$

6. With figure 4 and $M_1 = 352\ lb_m$:

   $B_1 = 0.011$ for aluminum

7. With figure 3 and $B_1 = 0.011$:

   $\Delta T_1 = 5.8°\ F$

Thus, a suit constructed with an aluminum shell 1.22 inches thick would have a mass of 352 lb_m and a 5.8° F maximum equilibrium temperature difference. However, larger temperature differences could exist during the time required for the suit to reach thermal equilibrium with its external environment.

Since the thermal diffusivity of most light metals is in the range of 3.6 to 4.4 ft^2/hr, the thickness ratio will be greater than one for $B>0.01$. Therefore, most light-metal suit thicknesses computed with the results of the first phase will develop small equilibrium temperature differences and be very thick and heavy. With this general conclusion the 5/8-inch-thick, water-filled shell proposed in the first phase becomes attractive since it would have a mass of 64 lb_m. The very large equilibrium and nonequilibrium temperature difference that would exist, since $\left.\frac{\rho}{k}\right|_{water} = 186\ \frac{lb_m\ hr\ °R}{ft^2\ Btu}$, could be reduced considerably by circulating the water.

SUMMARY AND CONCLUSION

The previously chosen hypothetical cylindrical space suit model has been analyzed to determine the maximum equilibrium temperature difference that would exist due to finite material thermal conductivity. The analytical suit model was subjected to a uniformly distributed metabolic heating and solar heating at one end. Numerical results were obtained for a range of thicknesses and suit materials. A comparison was made between the required thickness of this analysis and that of the first phase of this investigation to determine which thickness should be employed in a suit design. An example problem demonstrated that suits constructed from light metals will develop small equilibrium temperature differences and be very heavy. Fabric suits would be even heavier if temperature differences were minimized. The considerably lighter, water-filled suit shell that was proposed in the first phase will develop large equilibrium and nonequilibrium temperature differences. However, if the water circulation rates required to reduce these temperature differences are practical, then the design approach is still very attractive.

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